In-Flight Skin Friction Measurements Using Oil Film Interferometry

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Introduction

Oil film interferometry (OFI) has been successfully applied to skin friction measurement on an aircraft in flight. Measurements during two flights of a Beech F33C Bonanza single-engine light aircraft were made at several locations on the wing's upper surface including the leading edge, mid-chord, and on the flaps. OFI is a direct skin friction measurement method that works by measuring the thinning rate of a line of oil placed on a surface subject to a shear stress. The technique has previously been demonstrated in low-speed, transonic, and supersonic wind tunnels.[1,2] The basics of oil film interferometry were first developed by Tanner and Blows in the 1970s.[3,4] A transparent oil

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placed on a surface exposed to the airstream is thinned by the shear stress acting on it. Subject to certain assumptions, the resulting oil film's thickness varies linearly near the leading edge of the film. The rate at which this thinning occurs can be related to the skin friction shear stress using lubrication theory. The original technique used laser light to create visible interference fringes formed between reflections from the air-oil and oil-surface interfaces.

A variant of the technique recently developed by Monson and Mateer, fringe imaging skin-friction (FISF), employs several innovations which make oil film interferometry simpler to use.[1,5] This technique makes use of readily-available mylar sheets for optical-quality model surfaces, more conventional illumination, and requires only a single, post-flight image. The interference patterns may be viewed directly or, with a modest amount of image analysis, may be used to obtain quantitative values for local skin friction.

Procedure

Mylar sheets are placed on the surface, providing suitable optical properties for measurements to be made without additional surface preparation. These mylar sheets, sold as coverings for model airplanes ("MonoKote", Top Flite Models, Inc., Champaign, IL), come in pre-cut adhesive-backed strips. The index of refraction of mylar is such that the light reflected from the oil-mylar interface creates a strong interference pattern with the reflection from the air-oil interface. Since the mylar has an adhesive backing, all that is needed to prepare the surface for skin friction measurements is to clean the airframe surface and attach the mylar. The mylar and adhesive are easily removed from most surfaces (stainless steel, aluminum, Plexiglas) after the test, provided this is done without delay.

With suitable diffusion, a mercury discharge lamp can be used in combination with a camera filter with an overlapping center-pass wavelength to create an interference fringe image for which the illuminating wavelength is precisely known. The light source is placed so that the light shining on the surface is as nearly-perpendicular to the surface as practical to create the interference pattern from which the fringe spacing is measured. Moving the light source and viewing angle off-normal reduces the accuracy of the measurement.

The interference images were photographed with a 35mm single-lens reflex camera with a green filter on medium speed black and white print film. A custom-built light box containing self-ballasted high intensity discharge mercury lamps (which have a strong green peak at 546.1 nm) was used to provide a large, uniform source of illumination. The negatives were then digitized and stored on a Kodak PhotoCD at a resolution of 3072 x 2048 pixels. These digitized images were analyzed using a personal computer. A machinists' scale placed on the wing for the photographs and the known width of the mylar were used to provide a length calibration in the images.

Measurements were made on two flights of the aircraft. For the first flight, a transparent oil with a nominal viscosity of

200 cSt was used. The oil used was a silicone-based oil available in a wide range of viscosities sold as Dow DC 200 Fluid (Dow-Corning Corp., Midland, MI). For the second flight, the same type of oil in a 500 cSt nominal viscosity formulation was used. Mylar strips were installed at six locations on the upper surface of the left wing and five locations on the upper surface of the right wing. Three smaller strips were also placed on the right flap. Lines of oil was applied to the mylar just before flight.

On the first flight there were a total of 34 oil lines, including 9 on the right flap, which was deployed for the duration of the flight. The second flight had 31 oil lines, with 6 on the right flap. With the exception of the upstream-most oil lines on the flaps (which disappeared into the wing when the Fowler-type flaps were retracted), an identical oil line layout was used on each flight. Most of these oil lines were applied normal to the freestream flow direction. However, on each flight, three oil lines were also placed at approximately 45° to the wing's leading edge. These lines, covering the upstream 30% chord of the wing at approximately mid-semispan, were for the detection of boundary layer transition. Because of the large change in magnitude of the shear stress when the boundary layer becomes turbulent, a large change in fringe spacing was expected.

To obtain quantitative information, an image constant (IC) was determined for each flight to relate the measured fringe spacing to the skin friction coefficient. Monson and Mateer showed that if the skin friction coefficient (Cf) is assumed to be constant for the entire flight, an image constant relating fringe spacing and skin friction may be determined.[5] This image constant (IC) is

$$IC = \frac{2 \cdot (n_o \rho_o \nu_o)}{\lambda \cdot \int_0^{t_{end}} q_\infty(t) \cdot e^{\{(S_0+R_o)[T(t)-T_{ref}]\}} dt},$$

where λ is the wavelength of the light creating the interference pattern and ν_o, ρ_o and n_o are the viscosity, density and index of refraction, respectively, of the oil at the reference temperature T_{ref}, taken from the manufacturer's specifications for the oil. R_o and S_o are calibration constants for viscosity and temperature. T is the oil temperature, taken as equal to the local surface temperature as measured by a surface-reading thermocouple installed on the left wing at about mid-chord, one-third of the distance from the fuselage to the wing tip. q_∞ is the freestream dynamic pressure, determined from the aircraft's airspeed and altitude which were continuously monitored and recorded manually.

The skin friction coefficient (Cf), defined as the local shear stress normalized by the freestream dynamic pressure, is equal to the measured fringe spacing multiplied by the image constant.

Results

The two flight profiles were designed so that the desired flight conditions were reached as quickly as possible, with minimum variation in angle-of-attack. The aircraft was then stabilized on condition for approximately 30 minutes. The longer the aircraft is at the desired condition, the smaller the effect of the take-off, climb, descent, and landing variations on the surface flow being measured. The aircraft then made its descent and landing as quickly as possible.

During the first flight, the flaps were fully deployed with a test condition of 80 knots at 5000 ft pressure altitude. This required a full-flap takeoff. A route for the flight was chosen to minimize turns, and the turns that were made were limited to coordinated turns with a maximum of 5° bank angle to maintain nearly-steady conditions. This flight lasted 32 minutes, with close to 30 minutes at the on-condition dynamic pressure.

For the second flight, the flaps were fully retracted and an airspeed of 120 knots at 5000 ft was selected. This flight was slightly longer than the first. Note that both of these flight profiles represent off-design conditions for this aircraft and were chosen for the convenience of demonstrating the OFI technique.

Good interference images were obtained from each of the two flights, including determination of transition location on the diagonal oil lines. At the transition location on the first flight, a laminar separation bubble was observed. Figure 1 shows an interference image of one of the diagonal oil lines from the first flight. The boundary layer is laminar with the C_f decreasing--a smaller fringe spacing indicating a smaller C_f--until a point is reached where the oil has flowed forward, which was interpreted as indicative of separation. Downstream of this, the boundary layer is turbulent. On the second flight, as seen in figure 2, transition occurs slightly farther aft, without any indication of separation.

Quantitative values for skin friction were also calculated from each oil line. Figure 3 shows the skin friction coefficient and uncertainty range for results from several mylar strips. The results shown are taken from several slightly different span locations, collapsed to a single curve. The associated uncertainties demonstrate the comparatively high degree of accuracy possible with this method of measurement with a very modest amount of work.

In producing quantitative results, there were four major sources of uncertainty: image analysis, run conditions, Cf assumptions, and oil properties. In most cases, the contributions from each of these sources were comparable. Uncertainties in the image analysis procedure varied from image to image. Beyond the uncertainty in the measured fringe spacing due to the finite number of pixels in the digitized images, camera mis-alignment and perspective distortion made significant contributions. Uncertainties in the run conditions come from not having an automated, continuous data recording, the use of the aircraft's flight instruments for measuring flight conditions and simply assuming the oil temperature is equal to the thermocouple reading The third source of uncertainty is the assumption that Cf remains constant for the entire flight. This is not true during takeoff and landing phases of flight. Finally, the manufacturer's specifications were used for the oil properties rather than testing the oil. For most data points, the uncertainties in the Cf measurements are estimated to be on the order of ±10%.

Conclusions

OFI proved easier to use in a flight test environment than anticipated, and good fringe images were obtained for each flight at nearly all oil line locations. Analysis of the fringe images yielded quantitative measurements of skin friction with reasonable uncertainties for most oil lines on each flight. The location of boundary layer transition was evident on each flight, and some regions of separated flow were identified.

Despite the relatively simple nature of the instrumentation and data recording used in this experiment, it was possible to obtain skin friction measurements over a large area simultaneously. This method offers the possibility of making detailed skin friction measurements in flight test more cheaply and easily than is possible with other methods.

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FIGURE CAPTIONS

FIGURE 1: Interference image showing boundary layer transition and separation bubble from flight one.

FIGURE 2: Interference image showing boundary layer transition from flight two.

FIGURE 3: Chordwise skin friction distribution at mid-semi-span location for flights one and two.